THE RETELLING OF

Io — The Ultimate Destination for a Volcano Lover

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RETELLER Marilyn Morgan

The Library's JPL Stories series has been drawing larger and larger crowds of the curious. Best to get here earlier to assure getting a comfortable spot, I was thinking, threading my way amongst the chairs. The featured storyteller, Rosaly Lopes, was directing several people, all clutching pieces of paper and looking rather conspiratorial, to certain seating positions. The reason for this became clear a little later.

Teresa Bailey of the Library's JPL Stories team introduced the storyteller. Rosaly Lopes is the Science Coordinator for the Near-Infrared Mapping Spectrometer (NIMS) on board the Galileo spacecraft. Her responsibilities include planning NIMS observations of Io, Jupiter's ferociously volcanic Galilean satellite. NIMS simultaneously employs imaging and spectroscopy, making it a powerful and flexible instrument for geological and atmospheric studies. Starting at JPL in 1989, Rosaly had the opportunity to plan observations for Galileo's 1992 flyby of the Earth–Moon system, but this was a prelude for the real prize — using NIMS for remote observations of Io's burbling calderas, fire fountains, magnificent plumes, and lava lakes.

So this is a little slice of heaven for a volcanologist — to participate in studies of the most geologically active body in the solar system, using a new type of science instrument (new in 1989, that is, when Galileo was launched) on board the first spacecraft to carry out long-term observations of a planetary system. Galileo has been studying the Jovian system since December 1995.

HOOKED ON VOLCANOES

A native of Rio de Janeiro, Brazil, Rosaly Lopes went to England at 18 to study astronomy at the University of London, graduating in 1978. Pursuing interests in planetary geology and volcanology, she wrote her 1985 Ph.D. thesis on a comparative study of volcanoes on Earth and Mars. She says that her life has been shaped by a love of space exploration and a love of volcanoes, and she is able to trace her memories and experiences along a grid of space missions and volcano studies, from childhood impressions of Yuri Gagarin's Earth-orbiting flight in 1961 to Voyager, Mt. Etna, Kilauea, Galileo — and finally Io. She joked that when the Galileo mission was proposed in the mid-1970s as the Jupiter Orbit Probe, some of the current flight team members were probably just learning to walk, or were, perhaps, not even born yet.

Rosaly was on her way to London about the time the Voyager mission started, and graduated a year after launch. Voyager 1 reached the Jupiter system in March 1979 and treated the world to numerous stunning images of the alien landscapes of Jupiter and the Galilean satellites. During its flyby, the spacecraft found a tenuous ring system around Jupiter, adding to the excitement. On March 8, as it was passing out of the Jupiter system, Voyager looked back to obtain a routine navigation image of a crescent Io from 4.5 million kilometers distant. When optical navigation engineer Linda Morabito examined the image, she spied an immense plume, rising more than 200 kilometers, puffing out from the limb of Io.

Two volcanic eruptions were seen in this Voyager navigation image of Io.

It was something fantastic: Voyager had discovered an active volcano on another solar system body, beyond Earth. That was Pele (so later named), and a closer look at the image revealed that Pele was one of two eruptions going on as Voyager zipped by Io; the plume from the second volcano, Loki, glowed in the sunlight. Free of impact craters and blotched with strange surface features, Io, with its blazing colors, inspired comparisons with a pizza — in fact, years later the Galileo project held an Io–pizza lookalike contest.

Voyager infrared scientists had independently decided, based on data from their infrared interferometer spectrometer, that there must be volcanic activity on Io; spectra analyses revealed sulfur dioxide over one of the hot spots. The ultraviolet experimenters had previously seen inexplicable variable sulfur emissions, and now here was a definable source. At Io surface temperatures, sulfur dioxide is a white snow. Voyager 1 images showed at least eight active volcanoes. When Voyager 2 passed through the Jupiter system a few months later and observed seven of the eight, Pele had calmed, but six others were still active. Ultraviolet data indicated that Loki's eruption had increased in size by about 50 percent since Voyager 1's observation. While Voyager 2 found no new eruptions, in July it captured a series of images of a crescent Io with several plumes bursting from the satellite's limb, illuminated spectacularly by sunlight.

Rosaly was in England, studying with John Guest, a planetary geologist whose specialty was studying volcanic mechanisms in different planetary environments. Guest was a member of the imaging teams of Mariner 10 to Venus and Mercury and the Viking mission to Mars, and later, the radar imaging team for Magellan to Venus. Guest sometimes missed classes as he dashed off to observe erupting volcanoes. Inspired by Voyager's discovery of activity on Io and Guest's enthusiasm and influence, Rosaly decided to switch from pure astronomy and extragalactic studies, eventually earning a Ph.D. in 1985 in planetary geology and volcanology. Meanwhile, she told us, Galileo's Principal Investigators were selected and instruments were being built for a 1982 launch. This was occurring as she was happily "traipsing around looking at volcanoes."

On her first field trip in June 1979 to Mt. Etna, the volcano obliged with explosive eruptions, lava fountains, and fiery lava flows that threatened nearby villages. Rosaly, now "hooked on volcanoes," described the experience of seeing these events as an awesome one. But there is, she warned, quite another side to volcano-watching that one should not forget: the most beautiful thing can be the most dangerous. About a month after the Mt. Etna activity seemed to have abated, tourists clamored for a closer look, so tour guides took advantage of their interest and escorted them to the summit crater that had recently erupted (Mt. Etna has four active summit craters, plus flank eruptions). Rosaly described how, as she watched from about a mile away, there was a sudden unexpected phreatic explosion from the crater. This event killed nine tourists. (Guided excursions to areas on Mt. Etna still take place. Despite continual warnings against unguided hikes, in May 2001 a solitary tourist, incredibly, decided to walk up and camp near the summit. Searchers found the tattered remains of her tent, and footprints leading to the edge of the Bocca Nuova crater — but none coming back. It was the same crater whose explosion killed the nine tourists 22 years before.)

Kilauea's Pu'u O'o vent eruption in 1983.

Around the time Rosaly was developing her Ph.D. thesis, Hawaii's Kilauea volcano provided another opportunity to study lava flows. In June 1983, lava fountains erupted as high as 470 meters above the Pu'u O'o vent in the east rift zone of Kilauea. The vent had been acting up since January, and the fiery show went on every few weeks, as lava fountains built up a cinder-and-spatter cone that finally collapsed in 1986 after growing to more than 250 meters above the pre-eruption surface.

ONE THING AND ANOTHER

As for Galileo, the 1982 launch date had slipped because of difficulties in readying the space shuttle, which was the spacecraft's launch vehicle. Technical problems had prevented the shuttle from being deployed in 1978 as originally desired by NASA. Among other things, this affected Galileo's planned trajectory, which included a gravity-assist from a Mars flyby. A solid-fuel inertial upper stage (IUS) to boost the spacecraft enough to get to Jupiter would now be required, and that meant taking up space in the cargo bay, which meant reconfiguring the spacecraft. (It was not possible to launch Galileo from an expendable because at that time NASA was determined to launch all its missions from the shuttle.) But Congress cancelled IUS development and ordered NASA to adapt the high-performance Centaur liquid-propellant booster for shuttle use. Now Galileo could be sent straight to Jupiter from the shuttle. Beset by internal and external political pressures, NASA elected to use an IUS instead (Congress had reversed its own earlier decision); then more politics intervened, and it was back to the Centaur again. During all this, the Galileo project at JPL planned and replanned, again and again. The shuttle became operational in 1982, and finally Galileo got a launch date of May 21, 1986. The spacecraft was scheduled for launch from the shuttle that followed STS-51-L — Space Shuttle Challenger.

Rosaly paused, and observed that the very tragic event of Challenger's explosion meant another delay for Galileo. In the strange ways of the universe, Galileo's long and torturous path to launch enabled the astronomer-turned-volcanologist from Brazil to complete her scholarly studies, come to JPL in 1989, and join the mission science team, placing her in the very enviable position of being able to study active volcanoes on another solar system body.

As we all know well, the Challenger disaster froze the American space program for a time. However, Galileo was tentatively rescheduled for a 1987 launch, still with the Centaur. Then NASA decided that it would not be possible to use the shuttle main engines at maximum thrust, meaning that the shuttle would not be able to lift the Centaur–Galileo payload. JPL redesigned the trajectory for an Earth gravity assist and a partially fueled Centaur. But the Centaur–shuttle marriage was not to be. NASA decided it was simply too dangerous to have a liquid-propellant bomb in a craft that might have to make an emergency landing with astronauts aboard. It was back to the IUS and another trajectory redesign.

With one thing and another, one would think that people would be pretty discouraged. But as Rosaly says, Galileo people just refuse to give up, and so "some clever guys in nav" developed the innovative, 6-year VEEGA (Venus-Earth-Earth gravity assist) trajectory. She remembers Bill O'Neill, the project manager, constantly carrying around viewgraphs to explain the gravity-assist design — once past Venus, twice past Earth. The spacecraft would have to leave its high-gain antenna stowed for longer than originally planned, shielded from the Sun during the time Galileo would spend in the inner solar system. Launched in October 1989, Galileo was scheduled to arrive at Jupiter in December 1995. Rosaly was working on planning NIMS observations in anticipation of receiving vast quantities of data. Everything looked good for Galileo now.

Flawless gravity-assist flybys of Venus (February 1990) and Earth (December 1990) were accomplished, but with tantalizingly little data because of the need to protect the high-gain antenna in stowed position and transmit and receive via the two low-gain antennas (one of which was permanently stowed after Galileo's inner solar system traverse). The high-gain antenna was scheduled for deployment in April 1991. The command to unfurl was sent on the 11th, and everyone was happily looking forward to receiving the enormous flood of data and images. But of course, that would have been too easy.

UNDAUNTED: GALILEO II

Galileo's high-gain antenna — a 4.8-meter dish framed by wire mesh stretched over 18 graphite-epoxy ribs, resembling an umbrella — partially deployed on command. Some of the ribs were, as eventually came clear, hopelessly stuck, despite many subsequent attempts to persuade, bully, tease, command, bake, cool, and "hammer" (by pulsing the deployment motor) them free. Communications were now only possible using the low-gain antenna, capable of transmitting at about 10 bits per second, compared with the high-gain antenna's data rate of 134,000 kilobits per second. Instead of receiving a deluge of thousands of images, the mission was contemplating waiting for hours for just a few images. Things looked pretty bleak, " but it was then," Rosaly says, "that I realized that I had really come to the right place." Indeed, it seemed that the word impossible was not in the vocabulary of the Galileo flight team — they simply decided they were not going to let the failure of the high-gain antenna stop them.

Galileo's high-gain antenna should have deployed to this configuration.

Galileo's computer had six 8-bit microprocessors with total memory of 384 kilobytes, and was programmed in assembly language. It processed about as fast as the Commodore 64, a gamester's computer of the 1970s that boasted 16 colors, 64K of RAM, and a 2400-baud modem. Most of the instruments were controlled by single 8-bit microprocessors. Tal Brady led an effort to reprogram Galileo's onboard computer to do image compression. One problem was finding programmers who knew assembly language, a low-level language one step removed from machine code. JPL Deep Space Network engineers worked with the project to develop innovative methods to squeeze everything possible out of the data. With onboard data editing capability, compression, and a method of packetization, plus upgraded Deep Space Network systems, the low-gain antenna's capability could be boosted to about 160 bits per second. Bill Smythe led the effort to upgrade NIMS, making it a more flexible instrument than before. "Galileo II," as the reprogrammed, no-high-gain-antenna mission was called, was highly dependent on using the onboard tape recorder to store data and play it back at opportune times and at a rate compatible with the low-gain antenna's capabilities. The recorder had already proven its worth at the encounter with asteroid Gaspra. It would be essential for capturing and replaying data from Galileo's atmospheric probe on December 7, 1995 — Jupiter arrival day.

JUPITER — BUT NOT IO

The NIMS team was eagerly planning for Jupiter Orbit Insertion (JOI), looking forward to the science they would get during the mission's only planned close flyby of Io. Two years were spent planning for JOI. Because all the instrument data had to go on the tape recorder, the science teams fought vigorously for every bit of that real estate, which amounted to just 109 megabytes. Rosaly recalled that during this intense period, she was awaiting the birth of her son Tommy. There was a critical meeting two weeks before the due date, and another one week after, and the baby cooperated fully — Tommy was literally "born between meetings."

JOI was incredibly important for the NIMS team. Rosaly was "feeling happy," anticipating that the Io observations at JOI would be the highlight of her career. In October 1995, many of the Galileo science team members were at a meeting of the Division for Planetary Sciences of the American Astronomical Society in Kona, Hawaii. In this idyllic setting, they received the disturbing news that Galileo's tape recorder had malfunctioned. Galileo had taken some images of Jupiter during the early part of the approach phase, and because Jupiter was near conjunction, it would take about a month to transmit a color image using the low-gain antenna (the compression software was not yet uploaded). So image data were stored on the tape recorder, and the recorder was commanded to rewind to replay the data. Telemetry indicated that the tape recorder failed to stop after the rewind command.

"This was," Rosaly said, "extremely serious." The tape recorder was the primary means for obtaining the probe data, and indeed, the mission without the high-gain antenna was dependent on the tape recorder for images. On October 20, the tape recorder was commanded to play back data, and it did, to everyone's considerable relief. It was surmised that the tape was stuck at the end of the recorded image of Jupiter for the 15 hours that the capstans spun instead of rewinding. The tape was wound forward 25 extra turns, burying the possibly damaged section of the tape, but sacrificing the October 11 Jupiter-approach image.

Now the Galileo project had to decide how to use the tape recorder at JOI. Image data required high-speed use of the tape recorder, which might cause it to malfunction again, jeopardizing the probe data. Should they record Io image data — or not? This was to be the only close flyby of Io during the primary mission. After this long journey, with its trials and tribulations, not to photograph Io would be a terrible disappointment. Well, people react in various ways under such stress, and one thing you can do is sing. The Galileo Not Ready for Real Time Players (who are actually singers), strategically placed in the audience, now stood to warble a rueful song whose lyrics someone wrote at the time. (The Players had started 11 years ago at Galileo launch, another very stressful period, "and now," Rosaly said "there's no stopping us.")

JOI to the World
(sung to the tune of "Joy to the World"

JOI to the world of Jupiter
We've come so far to see
The glory of its atmosphere
The shape of its magnetosphere
And the wonders of its moons, we'll get the data soon
And wonder just what was lost by project goons.

Data to Earth will soon arrive
To give the tools to solve
The mysteries born of Voyager
And ground-based observations
On the way the cloud tops move, and the plasma can improve
The number of models that cannot be proved.

At this juncture in the mission, Bill O'Neill, the project manager, made what he called the most difficult decision of his career, and while it was a prudent decision, it was not a popular one. There would be no images of Io at JOI — it was simply too risky. The probe data had to be safeguarded. On Jupiter arrival day, JOI was just about perfect, and the mission obtained 75 minutes of probe data, plus data from the fields and particles instruments and the magnetometer. The disappointed NIMS team had to stand by as Galileo came within 900 kilometers of Io, dashing by like a tourist out of film on the way to the next attraction. This was the occasion for another remorseful tribute to the vagaries of space exploration, this one dedicated to missing Io.

Io, Io
(sung to the tune of "Hi-ho, Hi-ho, It's Off to Work We Go")

Io, Io,
It's down the drain you go
The tape was stuck, we're out of luck
Io, Io, Io

Io, Io, it's sad to see you go
We got no vote
So on that note
We go, we go on past

Io, Io, it's on the tour we go
We passed you by
The PIs cry
Oh no, we're missing our

Io, Io, we're losing lots of dough
The Io pics were just deep-sixed
Io, Io, Io

Io, Io, it's insidious I know
You'll sing this song
Near all night long
Oh no, oh no, oh no....

HOT SPOTS ON IO

The first distance observations of Io made by NIMS were made in June 1996. NIMS found many new volcanoes, but it was not easy. Rosaly remembers waiting for the first low-resolution, distance data, thinking that while not high resolution, "even so, it's still data" — but the data were scrambled. The radiation environment had corrupted the software. Eventually someone figured out how to descramble the data, and there they were — about 11 new hot spots. (More than 40 new hot spots were eventually found, and even more have been discovered in subsequent Io data.) "NIMS," noted Rosaly, "is an ideal instrument for finding hot spots; it is a better heat seeker even than my cat!"

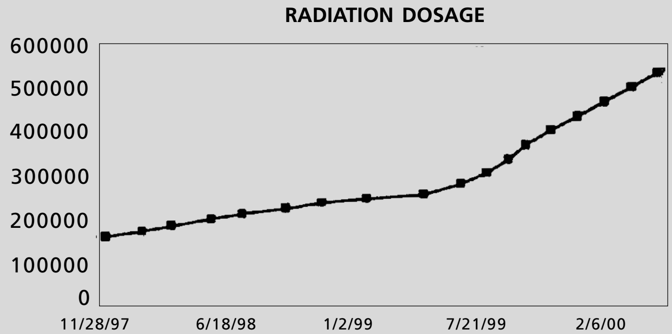
Rosaly showed us a comparison of Io data from Voyager, Galileo, and ground-based observations "with big error bars." Just about every spot on Io has thermal emission. Io has about 100 active volcanoes that we know of, and there are probably about 300, named after gods and goddesses of fire, thunder, and volcanoes — Rosaly mentioned that she was able to contribute some Brazilian nature god names to the pyrotechnic roster. Io's volcanoes change over time, and Galileo has proven useful for temporal measurements so we can see how the hot spots vary. In just a few months there can be major eruptions. Combined observations by NIMS and the camera revealed places on Io where the temperature reaches as high as 1800 kelvins (for comparison, Hawaiian volcanic activity generates temperatures of about 1400 kelvins). Rosaly told us that temperatures that high have not been seen on Earth for billions of years, in ultramafic magmas. We are not sure if Io lavas have the same composition as Earth's ultramafic lavas, but the temperatures are consistent. We have not been able to observe these types of lavas erupt before, but Io showed them to us.

After the primary mission ended in December 1997, NASA approved an extended mission, with Io studies on the schedule. The high levels of radiation near Io were dangerous for the spacecraft. In fact, said Rosaly, "we thought Galileo might die." Still, the project now planned for two Io flybys, in October and November 1999. With all the things that had happened, the teams had become philosophical, Rosaly says; as someone once observed, Galileo makes you want to convert to Zen Buddhism.

Planning in 1999 was friendlier among the science team members, Rosaly remarked. "We had seen how much more we got by making joint observations (NIMS, the photopolarimeter-radiometer, and camera) and putting data sets together. At the end of the Europa mission, we got even more when the Cassini and Galileo spacecraft were both at Jupiter together." That was the Millennium Mission, a name suggested by Rosaly. Talk began about the possibility of a third Io flyby. The project manager, Jim Erickson, said OK, but here's what we need — we need a lot of luck. Rosaly showed us what they were up against with a viewgraph (I-25 = Io flyby / 25th Jupiter orbit).

L U C K

- Radiation dosage with time says we are pushing our luck for I-25 — 408 krad versus 300 krad probable capability; 150 krad design
- X-26 is pushing it much further — 441 krad
- X-27 is shoving it out the door — 474 krad
- But … why not be ready if we get good luck! We've had a lot so far.



The spacecraft, designed for 150 krad radiation dosage, could "probably" handle 300, and maybe even 474 krad. And so they planned for it. The luck would have to take care of itself.

AT LAST — IO FLYBY DATA

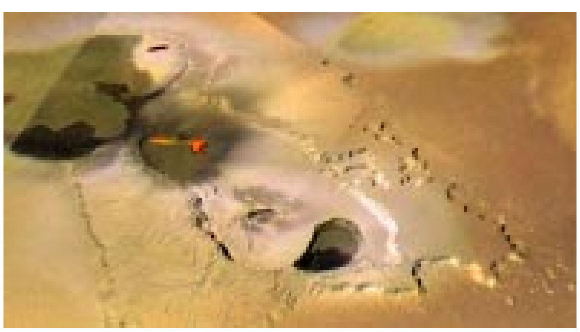
Because Galileo has to use its low-gain antenna plus the tape recorder to obtain and relay data, the instrument teams have to wait for some time to get data playback, so there's no point in hanging around during encounters anxiously gazing at monitors the way the Voyager teams did. At I-24, the camera team was going to get first crack at the data, so Rosaly and other NIMS team members departed for a science conference in Italy. However, the camera images were scrambled, so NIMS data were played back instead. The e-mail message Rosaly received from JPL shouted, "We've got Io data!" This was far too important to miss, so Rosaly, Bill Smythe, and two other NIMS team members fled the conference banquet, taking Bill's laptop to the hotel. With the appropriate tools ("Bill always carried screwdrivers"), they reengineered the room, using a rotary dial phone to make the connection. At last — Io flyby data! At 3:00 in the morning, they had their first NIMS spectra from Io. Celebrations were in order, but the hotel clerk was suspicious. Rosaly had gone upstairs with three men, carrying a keyboard, among other things; a few hours later, she happily comes down to buy brandy. He would not sell it to her, and so they toasted Io with mineral water. Showing the data the next day, she told us, "was one of the happiest days of my career."

Rosaly summarized some of Galileo's observations of Io, considered the most volcanic body in the solar system because its volcanoes put out the most heat. Loki Patera, the most powerful volcano in the solar system (more powerful than all Earth's volcanoes combined), has dark material and an island in the middle; probably it is a lava lake. Loki's eruptions are so enormous that they can be seen by Earth-based telescopes. One of the big mysteries in the distance observations of Prometheus was a wiggly lava flow that developed in the approximately 20 years between the Voyager and Galileo missions, with a plume that appeared to have "wandered" some 75 to 95 kilometers. Volcanoes on Earth don't get up and move, at least not so quickly, so what was going on at Io? The volcanologist Susan Kieffer surmised that hot lava flows out from the main vent over a frozen surface of sulfur dioxide frost, vaporizing the sulfurous "snow." The interaction between the reservoir and the flow creates an explosive plume, detected by Galileo, which was why the plume appeared to have moved away from the caldera — it was following the lava flow. NIMS observations showed two hot spots, one coinciding with the Voyager-era plume, the other at the location of the currently active plume. The Voyager-era hot spot has a higher temperature than the new plume hot spot, indicating the lava vent.

On I-24 in October 1999, Galileo took a daring pass that took the spacecraft as low as 611 kilometers above Io. Jupiter's intense radiation degraded some of the image results, but images taken in different camera modes were successful. On the next orbit, I-25, the spacecraft began safing about four hours before its scheduled closest approach of 300 kilometers above the surface in late November 1999. Urgent telephone calls to flight team members, many of them at home celebrating Thanksgiving, resulted in another Galileo triumph as –they sped off to the Laboratory to send new sequences, which were received and executed by the spacecraft about four minutes after the closest approach. The flight team was prepared for radiation-caused anomalous events because of the experience on I-24, and their quick response enabled Galileo to complete more than half its planned observations. Joe Boyce at NASA Headquarters, when hearing of the successful recovery, remarked that flight teams who have worked together on long missions get very good at quickly resolving anomalies.

On the November pass, Galileo captured images of Tvashtar Catena, a chain of volcanic bowls, revealing "fire fountains" of lava, similar to those of the Hawaiian volcanoes. As Rosaly said, "We did get amazing data, and the spacecraft didn't die! It was a big surprise." By combining infrared observations made by the NIMS and visible data from the imaging camera, we gained insights into interactions among thermal output, sulfur dioxide frost, volcanic plumes, and relationship to surface colors. (To see images of I-25 or any orbit, go to the Galileo website at http://galileo.jpl.nasa.gov, click on Images, then on Jupiter or your moon of choice. Images are grouped by both science objective and by orbit.)

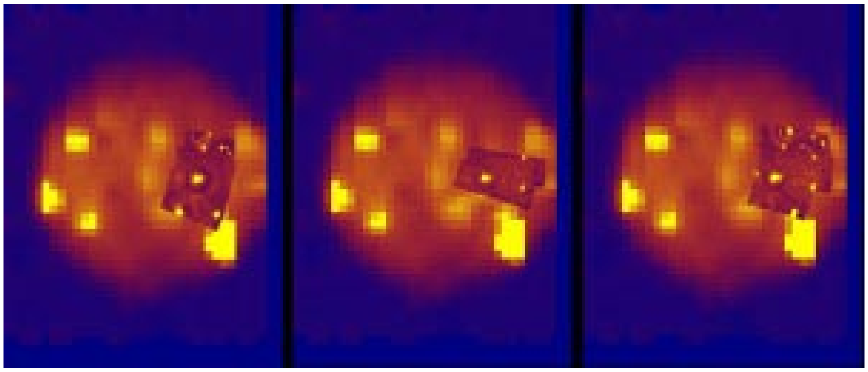
Fire fountains at Tvashtar Catena.



December 1999 was the start of the Millennium Mission, consisting of joint observations by Galileo and the Cassini spacecraft. Cassini's gravity-assist flyby wouldn't occur until the end of December 2000, when it passed above the cloudtops at about 10 million kilometers and had its speed relative to the Sun boosted by 2.2 kilometers per second. Images were released in March 2001 of joint observations by the two spacecraft, revealing a new plume emanating from Tvashtar Catena near Io's north pole. The new plume is about 400 kilometers high, nearly the same as a long-lived plume from Pele, which is near the equator. Although about 15 active plumes near the equator were detected by Voyager and then Galileo, the Cassini–Galileo images were the first of an active plume over a polar region. But we are getting ahead of the story.

February 2000 was I-27, the third Io flyby with remote-sensing data (the JOI flyby was not imaged). Rosaly noted that "We didn't think it was going to happen; it was way off the charts in terms of radiation [exposure]. But in fact, it was the most successful of the three Io flybys, and nothing went wrong." Nothing went wrong! — and this despite Galileo's increasing resemblance to a bungee jumper madly leaping through extreme radiation in fearless pursuit of science data. On I-27, Galileo passed within just 200 kilometers of Io's surface. The NIMS imaged a number of hot spots, seeing very high temperatures, consistent with ultramafic lavas.

NIMS can actually see the structure of lava flows. NIMS data overlaying Voyager imagery of the Pele region show temperature variations, with the hottest flows registering at about 1400 kelvins, or 2000 degrees Fahrenheit. Then there is Amirani, sporting the longest lava flow in the solar system.

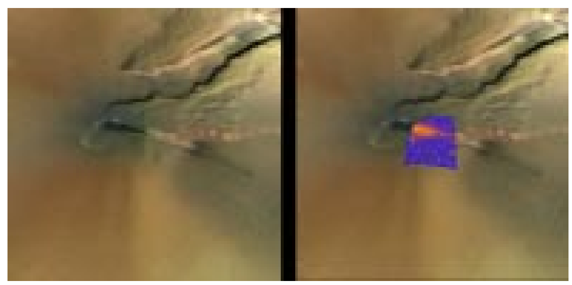


NIMS images of hot spots on Io taken on I-24, I-25, and I-27.

Its compound flows show younger dark areas that are not yet covered with sulfur dioxide frost. The Amirani lava-flow field spans more than 300 kilometers, with individual flows within it several kilometers long, about the size of the entire active eruption at Kilauea. Amirani's new lava flows covered about 620 square kilometers in less than five months.

The Io observational context continued to increase, enabling comparisons of Galileo I-24 images and earlier with those made of Prometheus during I-27. The I-27 images indicate that lava has been erupting onto large flow fields via a number of breakouts. Rosaly noted that Prometheus is characterized by a tube-fed flow, very well insulated: it is hot near the vent; then the temperature drops away from the vent, and ramps up again where lava breaks out. NIMS found many hot spots on Io, but the temperatures vary. Again, multi-instrument observations using the NIMS, visible imaging camera, and the photopolarimeter-radiometer (PPR) were valuable in understanding Io's complex volcanic phenomena, as were comparisons between Galileo and Voyager observations. High-resolution NIMS images taken during I-27 can be superimposed on earlier lower-resolution Galileo NIMS data to clarify data on volcanic activity and hot spot changes over time.

The successful Io flybys brought fame and glory as well as science data to the team — and, Rosaly beamed, the mission was honored with a *Science* magazine cover. The "Galileo: Io Up Close" section in the May 19, 2000, issue includes the article describing the wandering plume, co-authored by Susan Kieffer, Rosaly Lopes-Gautier, and others. (It is accessible via the JPL Library's electronic journal collection via http://beacon from JPL computers.)



NIMS temperature map of Pele during I-27 (superimposed on a Voyager image). Purple indicates cooler material.

ANTICIPATING GALILEO'S END

What next? Galileo's instruments have suffered, owing to having endured more than triple the cumulative radiation exposure for which they were designed. For example, the NIMS grating has become stuck, limiting the number of wavelengths available. Yet, the instrument continues to gather useful data. Three more Io flybys are planned, but Rosaly notes, "only two good ones." They are in August and October 2001, with remote-sensing observations planned for the imaging camera, NIMS, and the PPR. (The following flyby, I-33, is planned for January 17, 2002, but curiously, funding for imaging has been withdrawn, despite the fact that Galileo will fly to within 100 kilometers of Io's surface, a good opportunity for high-resolution imaging.) In honor of the return to Io in fall 2001, the Galileo Not Ready for Real Time Players regaled us with one last song:

The Io Torus
(sung to the tune of "Livin' La Vida Loca" by Ricky Martin)

It came up in mission planning
Gotta get back to I-o
NAV showed we had propellant
NA-SA gave us the dough.

We're coming up on Io
Yes, the sequence's nice and neat
But that won't make a difference
Once we cross the plasma sheet
And it kicks us in the seat!

[Chorus]
Ra-di-a-tion's high
Inside the Io torus
Will A-A-C-S die
Inside the Io torus?

WAKE UP! 'cause we're in safing!
Another night of hell.
Clock ticks! All are counting,
But in the end it turns out well.

We made it through encounter
But our memory has a bruise
If we can't work around it
Then surely the pictures we might lose
That would SURELY make the news!

[Chorus]
Ra-di-a-tion's high
Inside the Io torus
Hear the flight team cry
Inside the Io torus.

The P-Is got their goods
Now they all adore us.
So we'll go back again
Inside the Io torus.
It will never bore us
Inside the Io torus.

Rosaly told us that now the end is near, so the question arose — when and how to kill Galileo. It has to be done, but there are planetary protection issues. There is a worry about Galileo striking Europa, for example, which could seriously compromise data for future missions that want to land there to search for a possible ocean and see what might lie beneath the ice crust. The current plan is that in August 2003, Galileo will be allowed to impact Jupiter. The dive into the atmosphere will be monitored only, with no telemetry.

In answer to an audience member question about the mechanisms that cause Io's dynamic volcanoes, Rosaly told us about a most beautifully timed science paper. Three weeks before the Voyager Io flyby, the one whose navigation image revealed that plume from the volcano later named Pele, a paper in Science magazine suggested that tidal stresses on Io might produce volcanism. Indeed, Io is locked in a tug-of-war with Jupiter, Europa, and Ganymede. The tidal heating models propose that heating in the interior drives the volcanoes, yet with all the observations so far, we are still short of understanding the data. There isn't enough information to tell if Io is like a very old Earth, or to determine the compositions of Io's lavas and volcanic gases, eruption durations, and so on. Galileo's limited coverage and low data rate, and its antiquated (and now compromised) instrumentation cannot yield enough information. The mission concept of a return to Io with a more sophisticated, radiation-hardened spacecraft is now a gleam in the volcanologist's eye.

In her final statements, Rosaly noted that it has been thrilling to work with the Galileo flight team, a "fantastic group of people that just didn't give up" — inventing the VEEGA trajectory, doing an outer-planet mission with no high-gain antenna, reprogramming the spacecraft in flight, rescuing an encounter sequence in hours, and resolutely pursuing a daring course of observations involving extreme radiation danger for the spacecraft.

It seemed impossible, she said, "but we still did it!" In fact, after Galileo, Rosaly jested, "we might all join … is it the Marines? …with their slogan, 'The difficult we do now; the impossible takes a little longer.'" *

** It was the motto of the Seabees during World War II.*

GALILEO MISSION TIMELINE

For perspective, here are some major events in the life (and eventual death) of Galileo (the orbits are named by the first letter of the satellite to be studied, followed by a number indicating the Jupiter orbit; e.g., I-24 = Io/24th orbit).

Galileo at Io (artist's concept).

- Mid-1970s — Mission studied as Jupiter Orbiter-Probe (JOP)
- November 17, 1977 — Approval of project by NASA
- August 1977 — Science payload and PIs selected
- 1979 — Voyager discovers active volcanism on Io
- May 1982 — Original planned launch, direct to Jupiter
- January 1986 — Challenger disaster
- January 1986 — Planned launch, direct to Jupiter (2 years)
- October 18, 1989 — Galileo launched from Space Shuttle Atlantis
- April 1991 — High-gain antenna fails to open
- July 1995 — Jupiter probe release
- October 1995 — Tape recorder sticks; then works again
- December 7, 1995 — Jupiter Orbit Insertion (JOI), Io flyby (no images)
- June 28, 1996 — First satellite encounter (G-1)
- December 1997 — Primary mission ends; start of Galileo Europa Mission
- October 1999 — I-24, Io flyby (the first with remote sensing)
- November 1999 — I-25, second Io flyby
- December 1999 — Start of Galileo Millennium Mission, joint Galileo–Cassini observations
- February 2000 — I-27, third Io flyby
- August 6, 2001 — I-31, fourth Io flyby
- October 16, 2001 — I-32, fifth Io flyby
- January 17, 2002 — I-33, Io flyby (no imaging)
- August 2003 — End of Galileo mission

WEBSITES OF INTEREST

- The main JPL Galileo website — http://galileo.jpl.nasa.gov
- Lowell Observatory Io volcanic activity page — http://www.lowell.edu/users/ijw/volnews.html
- Galileo experiments and data at National Space Science Data Center — http://nssdc.gsfc.nasa.gov/planetary/galileodata.html
- Hawaii Center for Volcanology history of the Pu'u O'o eruption — http://www.soest.hawaii.edu/GG/HCV/puuoo_history.html
- Mount Etna history and eruptions — http://www.geo.mtu.edu/~boris/ETNA_intro.html
- USGS site on Hawaiian volcanoes — http://vulcan.wr.usgs.gov/Volcanoes/Hawaii/
- USGS site on Cascades Volcano Observatory — http://vulcan.wr.usgs.gov/
- USGS site on volcanoes — http://geology.er.usgs.gov/eastern/volcanoes/